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On the contribution of modelling to multifunctional agriculture: learning from comparisons

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Abstract

In this paper a set of criteria is proposed for the evaluation of the potential contribution of modelling tools to strengthening the multifunctionality of agriculture. The four main areas of evaluation are (1) policy relevance, (2) the temporal resolution and scope, (3) the degree to which spatial and socio-institutional scales and heterogeneity are addressed and (4) the level of integration in the assessment of scientific dimensions and of the multiple functions of agriculture. The evaluative criteria are applied to the portfolio of modelling approaches developed and applied in a joint project of the French research institute INRA and the Dutch Wageningen University & Research Centre.
The CLUE-S model focuses on prediction of changes in *multifunctional land-use* at regional scale, given a set of predetermined scenarios or policy variants, e.g. for ex-ante policy assessment and initiation discussions on regional development. The two other modelling approaches are complementary and aim to address *multifunctional farming activities*. The Landscape IMAGES framework generates a range of static images of possible but sometimes distant futures for multifunctional farming activities in a small region or landscape. It supports the exploration of trade-

offs between financial returns from agriculture, landscape quality, nature conservation and restoration, and environmental quality. Co-Viability Analysis generates viable trajectories of changes in farming activities within a given set of constraints, to reach a desired future. In the application implemented in the project, co-viability analysis focuses on grassland grazed by cattle which is also the breeding habitat of two wader species at field level.
The three modelling approaches differ in their policy relevance, in the ways that spatial and socio-institutional scales are addressed and in their levels of integration, but jointly cover most of the desired capabilities for assessment of multifunctionality. Caveats were particularly identified in the integration of the socio-institutional dimension and the related heterogeneity. Although the model portfolio did not completely satisfy the demands of the of the set of evaluative criteria, it is concluded that, due to their complementarities, in combination the three models could significantly contribute to further development and strengthening of multifunctionality.

Keywords: multifunctionality, modelling, exploration, solution space, scales, policy.

1. Introduction

1.1 Multifunctional agriculture and the transition-oriented approach

Over the last two decades, awareness of the limited sustainability of the European food and farming sector has increased due to problems encountered with overproduction, global trading obligations, environmental deterioration, urbanisation and growing public unease over food safety (Clark, 2006). Multifunctional agriculture (MFA) has been acknowledged to have the potential to contribute significantly to the mitigation of these problems (Losch, 2004). As a consequence, attention in policy, land-use planning and research directed at intensively managed agricultural areas in North-Western Europe has shifted from production to provision of multiple services and functions by agriculture, such as maintenance or improvement of landscape structure, sustainable management of renewable natural resources, preservation of biodiversity and contribution to socio-economic viability of rural areas (OECD, 2001; Durand and Van Huylenbroeck, 2003; Sattler et al., 2006).
In an attempt to arrive at an overarching perspective on multifunctionality, Renting et al. (this issue) propose a transition-oriented approach, which recognizes that multifunctionality does not refer to a static state-of-affairs, but can be considered as a transition-oriented and dynamic process. Modelling approaches can play a role in further strengthening multifunctionality by providing goals and possible futures and by establishing trajectories of desired changes to reach desired futures. The whole set of

possible future development options, each characterized by a specific allocation of resources, land-use or land management activities, can be characterized as the *solution space*. Modelling approaches can be categorized based on differences in information content of their results, which is defined here as the fraction of the solution space that is actually explored. These fundamental differences in output have their origin in the way the problem is modelled. The methodological choices have a profound effect on potential insights in options for MFA, and have a bearing on the way that results are assumed to be used in policy and planning processes (Rossing et al., 2007).

The transition-oriented approach identifies three additional fundamental notions that are crucial for conceptualizing multifunctionality (Renting et al., this issue): (i) agriculture is understood as the co-production of social, cultural and natural capital, (ii) multifunctionality is not created at a certain hierarchical level or scale, but results from the interaction between hierarchical levels (field – farm – landscape – region), and (iii) for realizing the full potential of multifunctionality, the recognition of the heterogeneity and diversity of not only bio-physical and ecological but also socio-institutional entities is important. These concepts should be acknowledged as essential elements in the formulation of frameworks for the evaluation, modelling and exploration of multifunctionality.

The concept of co-production refers to the interwoven character of agriculture, landscape and biodiversity (Van der Ploeg et al., 2004), and the functions and services they provide to society. The relations between the functions are often complex and difficult to define. Functions that are characterized by neutral interactions can co-exist without any hinder to or benefit from each other. In competitive interactions, two functions hinder each other and thought needs to be given as to how these functions can optimally co-exist. In synergetic interactions functions benefit from each other's presence. The challenge for modelling approaches aiming to contribute to multifunctional agriculture is to clarify the interactions between functions, which determine the shape and size of the solution space, and to contribute to further development and strengthening of functions exhibiting synergy.

Interaction between hierarchical levels determines the creation and development of multifunctionality (Knickel and Renting, 2000). For example at regional level, multifunctionality can be found in the combination of dairy farms with agro-tourism and nature conservation, where the agglomeration of farms, farm lands and semi-natural landscape elements provides an attractive environment for recreation and wildlife. At field level multifunctionality can be achieved by combining cattle grazing and meadow bird conservation within the same field, but nature protection on single fields or farms does not enhance biodiversity (Kleijn et al., 2001), whereas modelling studies show that biodiversity can benefit from the spatial clustering of such protective measures at landscape scale (Geertsema, 2002). Moreover, time scales of agricultural production and other functions are often very different. For example, farming activities take place at a time scale of several hours to several days; crops grown on a particular field can be changed year after year; nature development takes place at time scales ranging from decades to a century. Therefore, modelling approaches for multifunctionality should be able to operate at multiple spatial and temporal scales, and incorporate various hierarchical levels.

The ways of unfolding of multifunctional agriculture are heterogeneous and diverse. At a regional scale, the demand, environmental circumstances and history will differ considerably from region to region. At a smaller scale, local circumstances will provide different opportunities for different developments, for example soil quality determines the potential for agricultural production or nature conservation and restoration. Besides bio-physical factors, a variety of social factors such as personal preferences and objectives plays an important role (Swagemakers and Wiskerke, 2004). Instead of a focus on standardization and generalization of agriculture under the modernization paradigm, the challenge for multifunctional agriculture is to capitalize on this diversity and to match the possible function combinations with personal, local and regional variation. Supporting modelling instruments should be able to accommodate such heterogeneity and diversity.

1.2 Overview of modelling approaches

The complexity of issues related to multifunctional agriculture necessitates the use of supporting methodologies and models to inform stakeholders and policymakers, to design alternatives and to explore scenarios for the future. A large number of potentially usable approaches and techniques are available for integrated assessment of MFA (see e.g., Rossing et al., 2007; Zander et al., in press). Here we present a short overview to indicate the types of models and related work for the three methodologies that we will compare in this paper: CLUE-S, Landscape IMAGES and Co-Viability Analysis. Modelling approaches differ in their information content, i.e. the proportion of the solution space that is explored. These differences are schematically illustrated in Figure 1 for two functions F1 and F2 with competitive interactions (for instance gross margin and nature value; see Section 3.2).

Predictive land-use models are highly suitable for developing a mechanistic understanding of processes in biological or social systems and their drivers. These models generate a development trajectory towards a single future on the basis of current understanding of processes. Predictive land-use change and evaluation models can be run for different sets of possible decisions or developments (e.g., Arheimer et al., 2004; Berger and Bolte, 2004; Münier et al., 2004; Holman et al., 2005). Such scenario analyses and alternative futures studies yield one or more discrete solutions (Figure 1a). However, scenario studies are not suited for systematic exploration of multiple futures for the determination of trade-offs between functions. The CLUE-S model falls into this category of models, focusing on the territorial level based on observed land cover maps and projected requirements for land cover.

In land-use planning, the various functions are often competing for the limited available space, requiring an exploratory approach employing multi-objective optimization. Two main approaches can be distinguished. Firstly, multi-objective problems can be transformed into mono-objective problems, either by aggregation of the normalized and a priori weighed objectives (Annets and Audsley, 2002; Hajkowicz et al., 2005; Marshall and Homans, 2006), or by optimizing one of the objectives while the other objectives are constrained to a minimum or maximum acceptable value. The latter approach can be used for exploratory studies by generating continuous areas of acceptable or nearly optimal solutions (Makowski et al., 2000; Van de Ven and Van Keulen, 2007) or complete trade-off curves (De Wit et al., 1988; Zander and Kächele, 1999; Mimouni et al., 2000; Sattler et al., 2006). For the analysis of land-use problems, optimization algorithms such as mathematical programming techniques can be extended with effects of spatial configuration at farm, landscape or regional scale (e.g. Wossink et al., 1999; Irwin and Geoghegan, 2001; Lankoski and Ollikainen, 2003; Roetter et al., 2005). Typical examples of the use of these techniques can be found in applications to land retirement or conservation planning problems (Van Langevelde et al., 2002; Marshall and Homans, 2006; Crossman and Bryan, 2006; Newburn et al., 2006; Strange et al., 2006).

The second option for multi-objective optimization is to optimize each of the objectives separately and generate a range of options for possible land-use changes, thereby making the trade-offs between the objectives explicit. Thus, the result of such exploratory approaches is not a single solution to be accepted by all parties involved, but a range of options to inform discussions and learning processes about the consequences of choices, addressing disparate perspectives of stakeholders involved. Some examples of the application of multi-criteria analysis and multi-objective optimization are available, for instance applied to the reserve design problem (Rothley, 1999, 2006; Sarkar and Garson, 2004; Moffet et al., 2005). Multi-objective methods based on heuristic techniques result in a set of discrete solutions. When used in combination with Pareto-ranking and selection, normalization and a priori weighing of objectives can be avoided (Matthews et al., 2005; DeVoil et al., 2006; Groot et al., 2007). Pareto-based multi-objective optimization attempts to explore the whole solution space to reach the trade-off surface between functions from a set of discrete solutions (Figure 1b). The Landscape IMAGES methodology that will be evaluated in this paper is typical for this category of models.

Alternatively, viability models aim to deal with discrete and continuous dynamical systems under state and control constraints (Aubin, 1991; 1997). They do not identify optimal solutions but an ensemble of viable solutions, which fulfil a given set of constraints. Usually, these constraints are formulated as limits or thresholds to be avoided, i.e., the biomass of a particular species should not fall below a given value. Constraints represent the good health of the system and can be fixed at different levels based on scientific knowledge but they can also be stated by precautionary principles or by objectives that are assigned for management purposes (Mullon et al., 2004). Applications of viability theory have been proposed by Béné et al. (2001) and Doyen and Béné (2003) for the management of marine resource, and by Tichit et al. (2004) for herd dynamics under climate uncertainty. In viability analysis a portion of the solution space is explored by obtaining discrete solutions within fixed minimum and maximum boundaries (constraints) for the functions (Figure 1c). This will be illustrated for the Co-Viability Analysis in this paper.

1.3 Objective

The objective of this paper is to explore the potential of modelling approaches to contribute to improving multifunctionality of agriculture. This is done by comparing and evaluating the three modelling approaches addressing changes in land-use and farming activities in relation to multifunctional agriculture. These instruments have been developed in the context of two joint INRA-WUR projects (2003–2007): 'Multifunctional Agriculture, from Farm Diagnosis to Farm Design and Institutional Innovation' and 'Sustaining multiple functions in the rural countryside'. We first present a set of evaluative criteria used to evaluate the modelling approaches. Thereafter, the aims, modelling techniques, implementations and typical results of each of the models used in the INRA-WUR project are outlined and confronted with the set of evaluative criteria. This is followed by a discussion on the effectiveness of methodological choices for addressing the fundamental notions relevant to multifunctionality.

2. Evaluative criteria

For the evaluation of modelling approaches we propose a set of criteria which covers the following focus areas: (1) policy relevance, (2) temporal scale, (3) spatial scale and (4) integrated assessment of functions.

To determine the relevance of the methodology for policy we use the distinction between policy development and planning as proposed by McIntosh et al. (2005). These authors define policy development as the process of establishing acceptable and desirable goals and end states, whereas planning is concerned with the determination of the pathway to reach a desired state within the policy bounds (McIntosh et al., 2005, p. 743). The agenda setting process of policy development is typically a learning and negotiation process dealing with unstructured problems (Turnhout et al., 2007) with many stakeholders involved, each with their own perspectives and preferences. Eventually the policy goals should be agreed upon. Scientific input can support this interactive and participative process by offering insight in the range of available options. The planning process to identify the most suitable pathway to reach the goals that have been agreed upon can be considered a moderately structured problem, which also involves negotiation (McIntosh et al., 2005; Turnhout et al., 2007), and where the availability of alternative options to choose from is also highly relevant. It can be concluded that for both policy and planning processes concerning multifunctionality approaches that effectively explore and visualize ongoing processes of change and possible solution spaces are the desirable.

The aspect of temporal scale is related to the aspect of policy relevance. Setting goals for desirable directions for the unfolding of multifunctionality can be expected to focus on a longer term than the planning of measures to reach the goals. Therefore, to determine the goals in policy processes, static pictures of the potential alternative futures may be sufficient as input for the policy process, whereas for shorter term development and change trajectories more mechanistic approaches that capture the dynamics of the relevant systems are more appropriate.

The spatial resolution and the extent to which heterogeneity is taken into account constitute a crucial element for the proper assessment of options for development of multifunctionality from the transition-oriented perspective. Multiple spatial scales should be involved since processes and functions emerge and have relevance at different scales. The heterogeneity in the bio-physical and socio-institutional environments should be taken into account and exploited where possible. Similarly, the different levels of decision/policy making should be taken into account and matched with the scales of analysis/modelling.

Since multifunctional agriculture is the result of co-production between socio-institutional dynamics and agricultural practice, landscape and biodiversity, integration between natural, technical and socio-economical dimensions could be considered to be crucial. The interactions between the various indicators stemming from the various dimensions (which represent the multiple functions of agriculture) should be made explicit. This enables the identification of development options that capitalize on the synergy between functions, whereas competitive interactions resulting in trade-offs should be input for negotiation in policy processes.

3. Model description and comparison

3.1 CLUE-S applied to La Plaine de Beauce (France)

3.1.1 Aim

The objective of this study is to explore the consequences of alternative scenarios concerning land requirements, spatial policies and location factors that operate at different scales (regional, local) on the development of land-use patterns at a local scale. Results from this analysis are relevant to inform researchers, policy makers, inhabitants and other local actors (Turpin et al., 2006).

3.1.2 Modelling technique

The research is carried out using the land-use allocation model CLUE-S (Verburg et al., 2002; 2008), which allows multi-scale representation of the land-use system. The model combines the evolution of land requirements at the regional level over a given period and specific location factors at the local level (like suitability for each land-use and spatial policies). Regional land-use evolution and specific location factors are determined exogenously from the CLUE-S model. There are several ways to determine such inputs to the model, ranging from deductive to inductive procedures (Overmars et al., 2007). In this paper, we choose to assess the regional land-use evolution with a French positive mathematical programming model, and, in the absence of local process knowledge on the exact role of the different location factors, we derived location suitability from empirical analysis (logistic regression) of the current land use pattern.

In the CLUE-S model, the probability of the occurrence of land-use type j at location i ($p_{i,j}$) depends on the suitability of the location for the land-use type. The total probability of the allocation of land-use type j at location i ($P_{i,j}$) is influenced by the relative modification elasticity (λ_j) and the iteration parameter (α_j):

$$P_{i,j} = p_{i,j} + \lambda_j + \alpha_j \qquad (1)$$

The iteration parameter α_j is used to modify the total probability of the individual land-use types to reach the aggregated land-use requirements at regional scale as demanded. The first iteration starts with the same α_j value for all the land-use types. The aggregated allocation of each land-use type is compared with the total demand. For land-uses having an allocated area greater than the demand, the parameter α_j is decreased and it is increased when the sum is smaller than the demand. The final value is determined iteratively. Moreover, location preferences and neighbourhood constraints can be introduced (Equation 2). These modify the total probability for land-use j in year t in dependence of land-use in neighbouring locations and other location preferences (like preferences coming from local taxes and subsidies) in year t^{-1}:

$$P_{i,j,t} = (1-\beta_j)p_{i,j} + \beta_j N_j L_{j',t-1} + w_j k_{i,j} + \lambda_j + \alpha_{j,t} \qquad (2)$$

Where:

β_j is a weight parameter for the neighbourhood effect for land-use *j*

N_j is a matrix of neighbouring effects parameters for land-use j (Verburg et al., 2004); this matrix describes the land-uses j' that influence j, and the distance at which this influence operates.

$L_{j'(t-1)}$ is the map of land-use for the year t^{-1}

w_j is the weight for localisation preferences

$k_{i,j}$ is the parameter preference for localisation of land-use *j* on location *i;* such additional location preferences may include the consequences on the actors' location preferences coming from taxes/subsidies for a specific land use or reflect a change in location suitability as defined in a scenario.

3.1.3 Implementation

Assumptions on the evolution for build-up areas derive from the French Ministry for town and country planning (DATAR, 2003). The scenario that is presented here depicts a quick increase of build-up areas in the case-study region, which is close to Paris, with new houses built relatively far from the existing ones because new inhabitants preferentially look for amenities rich areas (Gude et al., 2006). As a consequence, the share of total agricultural area decreases. To quantify demands at the regional scale, we used results from a positive mathematical programming study presented by Barkaoui and Butault (2004), which presented the evolution of agricultural land-use for all regions in France under several decoupling options for European agricultural products over a 15-years period. Here we used the result of the complete decoupling option: the decrease in total agricultural area occurred mostly at the expense of cereals and slightly at the expense of pea growing or oilseed acreage.

In a sub-area named the Ogare zone, located in the North-East of the study area (Figure 2a), an Agri-Environmental Scheme (AES) was implemented in the presented scenario. This AES proposes measures aiming at: (i) the implementation of grass strips along fields devoted to cereals, oilseeds or peas, (ii) favouring a mix of patches of different crops (to avoid large monoculture areas), and (iii) increasing the area of forest. The schemes are implemented in two steps: the first 5 years are devoted to an increase of the total adoption area (after this time lag, the agri-environmental coverage should be of 75% of the Ogare zone), while the remaining 10 last years only consist of maintenance. For modelling the introduction of the AES two additional land use categories are introduced: 'env1' are cereals with grass strips that favour partridge nesting and 'env2' are oilseeds with the same kind of grass strips. For the first five years of the scheme, the land requirements for these two land use types increase. During this period urban zones and woodland areas for recreation are expected to increase as well. During the period from the 6th to the 15th year, only the requirements for urban zones increase (mostly at the expense of cereals). Neighbourhood constraints have been added: new urban zones are considered to be building at the distance of at least one pixel (250 m) of old urban zones and large patches with the same agricultural land-use type are prevented. To represent the region specific stimulation of land use types 'env1' and 'env2' as part of the Agri-Environmental Scheme (AES) the allocation of these land use types has been constrained to the Ogare zone.

3.1.4 Results

Figure 2 demonstrates the evolution of the simulated land-use pattern. The main city of the region is Chartres, which is located NW of the area. There are several small villages, scattered all over the area (see Figure 2b). Small forests edge rivers. Most of the area is devoted to crops (cereals, oilseeds, peas and vegetable) with very large fields for cereals and "smaller" plots for oilseeds and peas (note that in the map, one pixel is equivalent to a 6.25 ha field).

At the end of the 5 year period devoted to a raise in the AES (Figure 2c), urban sprawl occurred as expected mostly around the main city. After this period, the NW part of the Ogare zone, which is more favourable for oilseeds, is totally devoted to a patchwork of cereals and grass strips (env1), oilseeds and grass strips (env2) and some peas. In this zone, all the candidate fields are converted to the agri-environmental measures. The NE part of the Ogare zone shows a contrasted evolution, with a mixture of cereals (non AES), cereals and grass strips (env1) and peas. Though the adoption of the AES is lower than on the northern part, the living conditions for partridge are greatly improved with a fragmentation of the landscape higher than expected. Indeed, this fragmentation is due to the special measures that favour mixes of patches of different crops in association with the adoption of env1 crop even if it is surrounded with non-converted fields. Last, the piece of the Ogare zone located from SW to NE shows a patchwork of new groves, converted cereals and oilseeds (env1 and env2 crops), peas, vegetables and grassland areas. The impact of the AES is greater in this area.

After ten years of scheme maintenance despite the increasing urban pressure (Figure 2d), occurrence of urban sprawl is mostly prevented in the Ogare zone, with an exception in the SE part of the zone where the AES has been less adopted in the previous period. The increase of the urban area occurred north of the zone, mostly around the main city and close to a major road. It should be noted that a municipality (located north of the zone) has an important urban development. This municipality combines several attractive factors, a motorway entrance and proximity of landscape amenities (forests and newly designed landscape in the AES). But the nearer municipalities, which are also close to the same motorway entrance, do not impose the same sprawl. In the same way, in the western part of the zone, despite a lack of major roads, urban areas increase close to a forest.

The main interest of the CLUE-S approach in our empirically based case study is to highlight that different combinations of preference factors can drive towards land-use (here it is specially evident for urban sprawl): in our case, for some municipalities, landscape amenities reveal to be able to compensate for lower transport facilities. Moreover, combining preference factors with neighbourhood constraints proved to be particularly interesting.

3.2 Landscape IMAGES applied to Northern Friesian Woodlands (The Netherlands)

3.2.1 Aim

The Landscape IMAGES methodology aims to make trade-offs between functions explicit, for instance concerning financial returns from agriculture, landscape quality, nature conservation and environmental quality. The method employs multi-objective optimization algorithms to produce maps of alternative allocations of farming activities to fields and of linear landscape elements to field borders. The results are used as input for discussions among farmers, landscape management organisations and other stakeholders in the case study region.

3.2.2 Modelling technique

The Landscape IMAGES approach assesses of the performance of a given farm or landscape is based on multiple criteria of gross margin, nature value, landscape identity and nutrient losses. Farming activities differ in their contributions to these performance criteria and activities on two or more spatial units may interact with respect to the performance criteria. Consequently, different spatial configurations of activities result in different values of the performance criteria. The exploration of the trade-offs between performance criteria, or objectives, is formulated as a multi-objective design problem, which can be generally stated as follows.

$$\text{Max } F(\mathbf{x}) = (F_1(\mathbf{x}),...,F_k(\mathbf{x}))^T \quad (3)$$

$$\mathbf{x} = (x_1,...,x_n)^T \quad (4)$$

Subject to i constraints:

$$g_i (\mathbf{x}) \leq h_i \quad (5)$$

Where, $F_1(\mathbf{x}),...,F_k(\mathbf{x})$ are the objective functions that are simultaneously maximized or minimized, and $(x_1,...,x_n)$ are decision variables that represent the activities allocated to the n spatial units. The decision variables can take on values from a predefined array $\mathbf{x} \in S$, where S is the solution or parameter space. Constraints (Equation 5) arise from the problem formulation, for instance by limitations on the inputs or outputs related to the activities. The evolutionary strategy of Differential Evolution (DE; Storn and Price, 1995) is applied to a randomly generated population of solutions to improve its average performance criteria generation by generation (Bergey and Ragsdale, 2005). During this iterative process, solutions are selected for each new generation on the basis of Pareto optimality. A set of Pareto optimal solutions consists of solutions that are not dominated by other solutions, when all objectives $F_1(x),...,F_n(x)$ are considered. Using this concept the solutions can be ranked by the following procedure (Goldberg, 1989): first the Pareto optimal subset is established. This subset receives the highest rank and is removed from contention. This procedure is repeated, and each next subset receives a lower rank, until all solutions have been ranked. Subsets with higher ranks have an increased probability of being maintained in the next generation.

3.2.3 Implementation

The Landscape IMAGES modelling approach (Groot et al., 2007) was applied to a case study area located in the Northern Friesian Woodlands, The Netherlands. This region is characterized by a small scale landscape on predominantly sandy soils with dairy farming as the prevailing land-use activity. On some farms a limited proportion of up to 5% of the area is used for forage maize production, while the rest of the area is occupied by permanent grassland, rotationally grazed and mown. The fields with an average size of 2 ha are often surrounded by hedge rows. In the selected case study area of 232 ha enclosed by roads most of the area belongs to three farms.

For the case study the territory at landscape scale was compartmented into land units representing agricultural fields (polygons) and field borders (lines coinciding with polygon borders). Agricultural production activities were allocated to the fields, and field borders could be occupied by a hedgerow or remain unoccupied. An agro-ecological engineering approach was used to design production activities, which are defined as the cultivation of a crop or vegetation and/or management of a herd in a particular physical environment, completely specified by its inputs and outputs (Van Ittersum and Rabbinge, 1997). The inputs and outputs of the production activities were calculated from established empirical agro-ecological relations (see Groot et al., 2007).

As indicator for the economic performance of farms, gross margin was adopted. The returns from production per field were calculated directly from the milk production and the milk price. Costs per field were separated into costs related to production (harvesting by grazing or mowing, fertilizer application and transport costs). The financial revenues from nature conservation packages were added to the value of the objective function for economic results. The applicability of conservation packages to individual fields was assessed on the basis of plant species abundance, and harvesting and fertilization regimes. Species abundance in the grass swards and hedge rows was used as an indicator for nature conservation value. The relationship between nutrient availability and average species presence in grasslands was derived on the basis of data of Oomes (1992). Landscape quality was related to variation in the landscape, calculated as the weighed sum of (1) the variance of the species number for each field and its adjacent fields and (2) the half-openness of the landscape, represented by the squared deviation from 50% occupation of the proportion of borders occupied by hedges. Emission of nutrients was calculated from the difference between uptake of N by grass and availability of N from natural soil fertility and fertilizer application.

3.2.4 Results

The solution set covers a large range of possible configurations of the landscape in terms of land-use on fields and the placement of hedges on field borders. The solution space for the objectives of economic profit and nature value is presented in Figure 3a. In this solution space, the collection of solutions that form the Pareto optimal frontier (rank 1) represents the trade-off between the objectives. Acceptable alternatives should be selected from this frontier, and can be discussed on their merits, which depend on the importance assigned to the objectives by the various stakeholders involved. Relations with the other objectives, that are not presented here, should also be considered. Figures 3b to 3e demonstrate the presence of hedgerows, the plant species numbers in grass swards and the nitrogen emission per field for two alternative solutions selected from Figure 3a. Nature value was higher for solution A than for solution B (Figure 3a), which resulted from higher number of plant species in grass swards and hedgerows (Figures 3c and 3e). Solution B had higher average gross margin than solution A (Figure 3a), but also nitrogen losses were considerably higher than for solution A (Figures 3b and 3d), which resulted in higher average emissions at landscape scale (98.7 versus 47.4 kg N per ha per year).

3.3 Co-viability analysis applied to Marais Poitevin (France)

3.3.1 Aim

An exploratory study of temporal allocation of grazing intensity was conducted to predict how to manage grassland in a way that simultaneously ensures a certain level of habitat quality and a certain level of agricultural production. It examines how livestock grazing, through its impact on habitat quality, may be used to sustain a bird community without penalizing livestock production. The model integrates simultaneously several goals (productive, economic and ecological) that need to be ensured throughout time. The multi-criteria approach is referred to as 'co-viability' analysis. Model outputs could be used in discussion with farmers and conservation managers to make them aware of the dual consequences of management.

3.3.2 Modelling technique

This study was conducted using a Co-Viability model (Tichit et al., to appear) based on Viability Theory (Aubin, 1991). Viability theory is a set of mathematical tools, which can be used to study how a renewable resource can be harvested over time in a sustainable way. Consider a simple dynamic system in which biomass represents the state space of the system and the harvest rate stands for the control or decision variable. The constraint set denoted K represents the thresholds on biomass and harvest rate that should be avoided in order to maintain the system in the long term. A first objective is to identify the levels of biomass B(.) that are associated with viable harvesting strategies h(.). This problem refers to the computation of the so-called viability kernel Viab (K) (Aubin, 1991). At a given time t0, Viab (K) stands for the set of biomass B(t0) such that there are harvesting sequences h(t0), h(t0+1), … , h(T) yielding biomass sequences such that the constraint set K is satisfied for every time greater than t0. For every state lying outside the viability kernel, each harvesting strategy yields a catastrophic situation through the violation of the constraints in finite time. Once the viability kernel is found, it is possible to compute the viable harvesting strategies h(t) using e.g. Monte Carlo simulations. Such h(t) exist as long as the state B(t) lies within the viability kernel Viab(K). Thus, rather than a unique optimal solution, a set of viable harvesting strategies are identified that result in trajectories of biomass which satisfy the dynamic resource use constraints. Sward height constraints between 5 and 20 cm in May and June were specified in order to create mixed habitat quality for lapwings and redshanks. It corresponded to sward heights including high and medium chick survival for both species.

3.3.3 Implementation

The model focuses on a grassland ecosystem which is the feeding resource of suckling cattle as well as the breeding habitat of wader species. As ground nesting birds, waders are extremely sensitive to sward height and grazing is a potential tool to manage habitat quality for these birds (Tichit et al. 2005a, b). The model comprises two interactive sub-models: the first sub-model describes the dynamics of a grass sward controlled through grazing; the second sub-model represents the dynamics of a simplified wader community composed of two species: lapwing (*Vanellus vanellus*) and redshank (*Tringa totanus*). Habitat quality defined in terms of sward height is the key variable that relates both sub models. Outputs in terms of sward height generated by the first model are incorporated as input into the second model where sward height is a factor affecting species survival rates.

Ecological constraints are defined by specifying minimal and maximal sward heights that determine the level of habitat quality for each bird species. The productive constraint includes considerations on livestock feeding requirement by imposing that total sward mass demand for grazing cannot exceed available biomass, introducing an implicit limit on cattle density.

Viability theory was used to determine the set of viable grazing strategies which ensure the compatibility of the dynamics of the grazed sward and ecological and productive constraints at any point in the future. The resulting viable grazing strategies are ranked according to an economic criterion, the feeding costs associated with each grazing strategy. Two different economic goals, representing the extremes of the potential viable grazing regimes are investigated:

(a) Minimization of discounted cost related to indoor feeding. Strategies associated with this objective cause maximisation of grazing since the minimization of indoor cattle feeding costs is equivalent to the maximisation of grazing, i.e. livestock units in pasture.

(b) Maximisation of discounted cost related to indoor feeding equivalent to minimization of cumulative grazing throughout time.

In contrast to strategies associated with objective (a), those satisfying objective (b) are less profitable from the production point of view but are likely to be more favourable to bird conservation as heavy grazing may penalize birds through nest trampling (Beintema and Musken, 1987). In this sense objective (b) favours conservation and ecological dimensions and it is referred to as 'ecologic grazing' whereas objective (a) is referred to as 'economic grazing'. To establish viable strategies for each objective, simulations were performed by iterating dynamics of sward biomass and wader populations over a period of 15 years.

3.3.4 Results

Dynamic programming results predicted that both ecologic and economic grazing were viable in the sense that maximising or minimising grazing generated a mixed habitat quality. For any initial biomass lower than 550 g organic matter per m^2, both grazing strategies satisfied the constraint set. This means that there was a large set of management decisions, bounded by the both extremes of grazing managements that yielded sward dynamics such that habitat and production constraints held true at all times. However, due to differences in grazing intensity and periods ecologic and economic grazing strategies were associated with contrasted effects on sward height and consequently on wader community persistence.

Ecologic grazing was characterised by low grazing intensity during late winter and early spring (Figure 4a) leading to high habitat quality for lapwings and redshanks (Figure 4c). Economic grazing corresponded to a higher intensity maintained throughout spring (Figure 4b) inducing a sequence of high followed by medium habitat quality or the reverse for both species (Figure 4d). Cattle density associated with each grazing strategy was always lower than maximal cattle density $u_{max}(t)$ indicating that cattle feeding requirements were always satisfied and that grass production was sufficient to sustain production across the time horizon.

The economic merit associated economic grazing was nearly three times higher than that of ecologic grazing (431 and 151 € $ha^{-1}year^{-1}$, respectively). However from the conservation point of view, both grazing strategies resulted in striking outputs in terms of community dynamics. With ecologic grazing, the wader community was maintained across the time horizon (Figure 4e) suggesting that even with limited grazing it was possible to ensure the maintenance of the wader community by creating high habitat quality for both breeding species. Economic grazing generated a habitat quality that was less favourable for the maintenance of the species as shown in Figure 4f where lapwing densities sharply declined over the 15 year time period. Although total extinction of the population never occurred as there was always high quality habitat for either redshanks or lapwings, these results suggest that maximising profit outcome whilst maintaining wader community is not possible.

3.4 Confrontation with the evaluative criteria

The position of the presented methodologies within the set of evaluative criteria is indicated in Figure 5. Landscape IMAGES would be suitable in the context of policy development, since it produces static pictures of potential future landscapes which could be realized in the long term, whereas the Co-Viability Analysis produces alternative, dynamic trajectories to reach a desired state within preset constraints (Figures 5a and 5b). Landscape IMAGES and Co-Viability Analysis are exploratory approaches, which yield a set of solutions that clarify a substantial proportion of the solution space (Figure 1). In contrast, CLUE-S can be used to evaluate policy scenarios (Figure 1a), resulting in dynamics in land-use at medium term, and therefore takes an intermediate position in the areas of policy relevance and temporal scale (Figures 5a and 5b).

The CLUE-S model was, in the presented cases-study, applied at the region scale, i.e. the largest spatial scale of the three methodologies. Landscape IMAGES integrated fields and farms to landscape scale, which can be considered as a sub-region, whereas the current implementation of the Co-Viability Analysis applies to one field (Figure 5c). The three models are able to take into account heterogeneity to a different degree. CLUE-S can account for spatial variation and the land-use allocation functions based on drivers of different dimensions, ranging from bio-physical to socio-institutional. Landscape IMAGES deals with heterogeneity in the bio-physical environment: in the current implementation a gradient in soil fertility in the case study region (Groot et al., 2007) and variations in the configuration of landscape elements. The Co-Viability Analysis takes account of temporal variation in the state variables and the selected management practice sequences applied.

The CLUE-S model incorporates the socio-institutional environment that are represented by drivers of land-use change, whereas in Landscape IMAGES and Co-Viability Analysis this is limited to the economic performance per farm or per field in terms of gross margin (returns minus variable costs). Therefore, CLUE-S can be considered as the most 'integrated' methodology, but is in contrast less rooted in disciplinary scientific knowledge, since it uses, in the presented case-study, statistical associations between land use and its drivers.. In an intermediate position, Landscape IMAGES addresses economic, ecological and cultural dimensions. The production activities used in Landscape IMAGES originate from a technical coefficient generator based on well-established relations between inputs (e.g., nitrogen fertilizer) and outputs (e.g. herbage production and plant species presence). At the other end of the spectrum, the Co-Viability Analysis is based on mechanistic models of the systems components relating to grassland productivity and bird population dynamics. By exploring (part of) the solution space, Landscape IMAGES and to a lesser extent the Co-Viability Analysis make interactions between functions explicit, which is not the aim of the scenario-based CLUE-S simulations (Figures 1 and 5d).

4. Discussion

The transition-oriented process of strengthening multifunctionality (Renting et al., this issue) is envisioned to be supported by research and modelling approaches that can provide insight in the window of opportunities, and the required choices concerning land-use and farming activities. These approaches can guide unfolding of multifunctionality by informing stakeholders in two ways: by suggesting goals and possible futures (policy development) and by establishing consequences of choices through mapping change trajectories (planning). The analysis presented in this paper has demonstrated that the three compared methodologies jointly form a complementary modelling portfolio (Figure 5), which can potentially contribute to the further development of multifunctional agriculture in policy and planning processes. Similar portfolio approaches involving multiple models and/or participatory tools have been demonstrated to be successful in projects focusing on problem solving in complex, multi-scale problems in socio-ecological systems (Young et al., 2006; Bohnet and Smith, 2007; Bouma et al., 2007).

In Landscape IMAGES the focus is on revealing the whole range of possible futures (cf. Figure 1c). Future images are generated without an explicit link to the current situation, but based on scientific and expert knowledge on ecosystem relations and processes. Although the results are hard to validate, they can be very innovative. Therefore, this approach can be useful in discussions on the alternative directions of multifunctional agriculture. Pathways from the present to these future images are not known. In CLUE-S the explorations have been carried out using a scenario approach (cf. Figure 1a). For a specific setting of model parameters an image of the future was generated together with the pathway describing the development from the present to the future. Different parameter settings will lead to different pathways, resulting in different images of the future. This approach can be suitable to determine the effect of policy measures or external developments on the course of future land-use patterns, thus informing for example policy makers to examine different future scenarios and to evaluate the impact of different policy measures and their effects and robustness under different scenario conditions. The presentation of results as maps revealed to be very informative for stakeholders in discussions about the anticipated future developments and the need for spatial policies (Turpin et al., 2006). The Co-Viability Analysis employs a contrasting approach. Instead of choosing the decision variable of the model and revealing an unknown future, a desired future and road to this future is defined by a set of restrictions representing the limits within which the system should be maintained in the future. Different mathematical tools allow computing the set of viable states and decisions leading to this future (cf. Figure 1b). The output of the Co-Viability Analysis is a set of possible pathways to a desired future image. This approach is particularly useful to involve stakeholders in a negotiation-based planning process in particular because constraints can be set at different levels depending on knowledge and priorities. Furthermore the viability concept offers an integrated criterion for multiple goals in a short to mid term perspective. It is a powerful tool for examining interactions between temporal scales and how different objectives may conflict in the future as a consequence of short term decisions.

The models differ in the way they address multifunctional agriculture and in their potential to contribute to the concept of co-production in the proposed transition-oriented approach to multifunctionality. The CLUE-S model has its roots in the *regional land use approach* to multifunctionality as described by Renting et al. (this issue). This approach strongly focuses on the territorial level based on observed land cover maps and projected requirements for land cover. Land cover is only indirect linked to actual land use and multiple land use functions. The land cover types co-exist in predefined proportions that can evolve along time, with predetermined non-spatial interactions: in Equation (1), the probability (p_{ij}) includes information on the way each local factor drives the land use pattern (and thus all the functions jointly). In the presented application of the model the selection of location factors is based on observed or hidden positive or competitive interactions between functions, which are translated in probabilistic relations: they are statistically significant but no information is provided on the causality relationships between driving forces and functions. The extension of the model with location preferences offers a method to allow functions to be influenced by respectively taxes/subsidies while neighbourhood interactions (Equation 2) allows functions to be clustered spatially. In case of sufficient knowledge of the causal relationships between location factors and functions it is preferred to replace the statistical technique by causal interactions (Overmars et al., 2007).

The Landscape IMAGES modelling instrument aims to reveal the nature of interactions between functions by exploration of trade-off curves (Figure 3) and thus enables the identification of synergetic interactions. Yet another contrasting approach to co-production is taken in the Co-Viability Analysis, which allows any type of interaction (synergy, competition and neutralism) as long as the predefined constraints for the performance of functions are not violated. Also in this methodology the interactions are not made explicit. Another interesting point is that the different types of constraints are taken into account without any a priori hierarchy among them. This aspect is a salient point if we consider that for the coming decades the priority between farming and biodiversity objectives remains to be defined

(Green et al., 2005).

The two models that are spatially explicit, CLUE-S and Landscape IMAGES, both allow interactions between hierarchical levels. In CLUE-S the interaction between regional demands and local preferences determine the outcome of the land-use allocation. In Landscape IMAGES the farming activities can be constrained at field, farm and landscape scale and functions may be evaluated at any combination of scales. These characteristics also support the introduction of heterogeneity and diversity in bio-physical environment, socio-institutional conditions and the resulting land-use or farming activity allocation. The implementation of the spatially explicit environment is different for the two models. CLUE-S has adopted the raster model by imposing a regular grid of square cells on the study area. The advantage of this approach is that the whole study area is divided into spatial units of equal size and equal shape, simplifying spatial representation of the study area and calculations in the model. A disadvantage of using equal sized raster cells is that spatial objects can not be modelled at different spatial resolutions. For example if a hedgerow and the bordering field need to be represented by equal sized spatial elements, many cells will be needed to represent the field, or the hedgerows need be represented in mixed cells. To avoid this complication, in Landscape IMAGES a vector environment has been adopted, representing the fields as polygons and the hedgerows as lines. Another advantage of a vector approach is that shapes of landscape elements can be variable throughout the study area, this enables to represent a landscape with considerable detail using a coarse resolution. The disadvantage is that the shapes of objects in the model are fixed. In a raster environment the shape of an agglomeration can more easily be changed by allocating other cells to the agglomeration. As in a raster environment the spatial resolution in a vector environment is determined by the processes to be modelled, the extent and the data availability.

The manner of modelling has also implications for the location specificity of outcomes. Modelling can base itself on ‘laws’ of economy and ecology and extrapolate from there, or can describe reality in statistical ways, with little knowledge of underlying processes. Both have their consequences for the role of the results. Statistics as used in CLUE-S are relatively straightforward, are not burdened with detailed knowledge of component processes and can handle technical and socio-economic aspects. Drawback is that extrapolation can only be done over short time spans, assuming that relations between variables do not change fundamentally. Also, causes of effects remain hidden. As a result, target audiences may be more policy makers than managers who are interested in causes. Bottom-up models, such as Landscape IMAGES and the Co-Viability model presented here, are generic and provide more insight in causes. The results may be less comprehensive and therefore less interesting to policy makers, but more so to managers who are used to integrating partial information themselves.

5. Conclusion

The three models employed within the joint projects of INRA and WUR are clearly complementary to each other in terms of the issues addressed and the target stakeholder groups. The Clues-S model supports multi-issue evaluation of policy choices and their repercussions for dynamics of land-use at a regional scale. Landscape IMAGES offers the opportunity to explore possibilities of multifunctional farming activities and landscape management by generating static images of potential futures, to inform multi-stakeholder discussions and decision making processes. The Co-Viability approach presents feasible temporal dynamics of changes in farming activities to reach a combination of future goals under uncertain circumstances. The three models differ in the degree of exploration of the solution space, the exploration of trajectories to desired futures, the representation of the spatial environment and the incorporation of interactions between spatial scales. None of the models fully satisfies the demands put forward to support the transition-oriented approach to multifunctionality, but in combination form a modelling portfolio that bears the potential to offer a significant contribution to further development and strengthening of multifunctionality from field to regional scale and at intermediate to long term time scales.

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Figure captions

Figure 1. Conceptual representation of the solution space defined by two functions F1 and F2 (shaded area) and the fraction that is actually explored (white area) by different modelling approaches. The symbols (○) indicate discrete solutions. a. Scenario simulations. b. Co-Viability Analysis, c. Multi-objective Pareto heuristics.

Figure 2. Overview of the case study area (La Plaine de Beauce, France) for the CLUE-S model with the Ogare zone in blue (a), and the original and simulated land-use distributions from the CLUE-S model: (b) land use map at the start of the simulations; (c) land use at the end of the time-lag devoted to a raise in the AES scheme (5 years of simulation) and (d) after 10 years of scheme maintenance despite an increase of the urban pressure (15 years of simulation).

Figure 3. a. Solution space (○) and Pareto-optimal frontier (●) for the relation between gross margin and nature value at landscape scale, generated by the Landscape IMAGES model for a sub-region of the Northern Friesian Woodlands (The Netherlands). Characteristics of the selected alternatives A and B are given in Figures b-e: nitrogen losses per field (kg N per ha ; b, d) and plant species numbers in grass swards (per 25 m^2; c, e) in landscapes A (b, c) and B (d, e). Shaded fields belong to the three farms; white fields indicate buffer fields, not belonging to the farms. The thin lines indicate unoccupied borders; the thick lines describe the presence of hedgerows.

Figure 4. Results from the co-viability model applied to Marais Poitevin (France). Mixed habitat quality generated through ecologic or economic grazing. Viable trajectories are plotted over 15 years including (a, b) grazing strategies (blue) and productive constraints i.e. maximal cattle density $u_{max}(t)$ (clear blue), both in livestock units ha^{-1} (c, d) sward height (black), where habitat constraints of lapwings (green) and redshank (red) are respected in May and June respectively (e, f) wader population densities for lapwing (green) and redshank (red). Every population is maintained through ecologic grazing whilst through economic grazing, lapwings decline and redshank population persists. In the simulation biomass is initialized at 100 g organic matter per m^2.

Figure 5. The position of the three models relative to the evaluative criteria constituted by areas of policy relevance (a), temporal scale (b), spatial scale (c) and degree of integration (d). The grey-scale gradient indicates high (black) or low (white) desirability of the attribute combination per aspect from a perspective of policy relevance of modelling for development of multifunctionality. The arrows indicate a gradient. See text Section 2 for explanation.

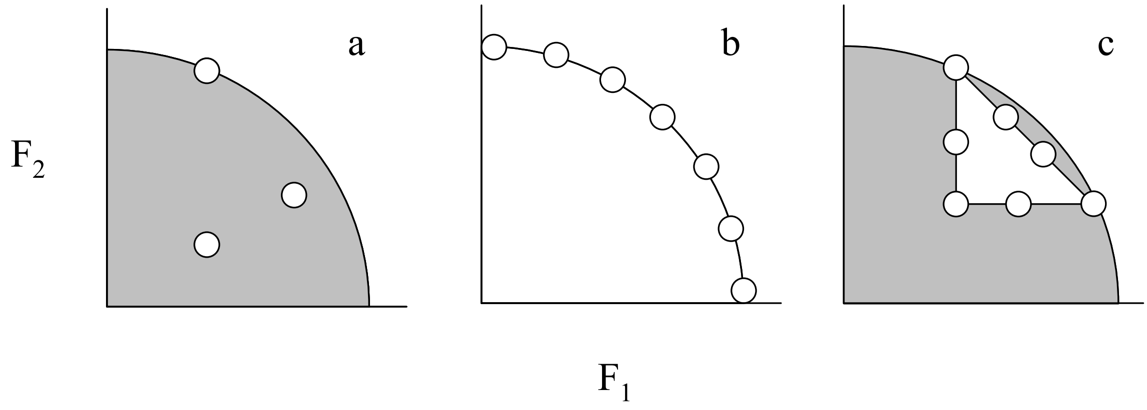
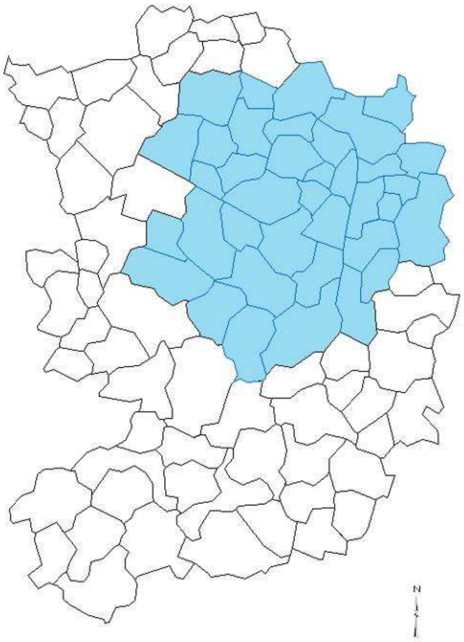
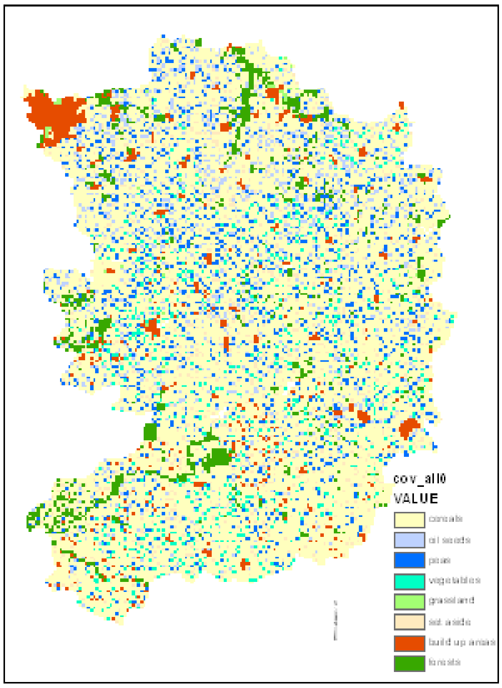


Figure 1.

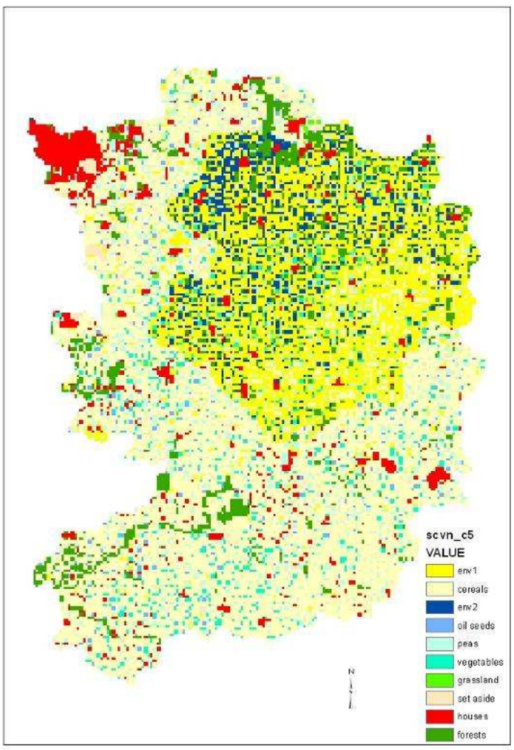
1



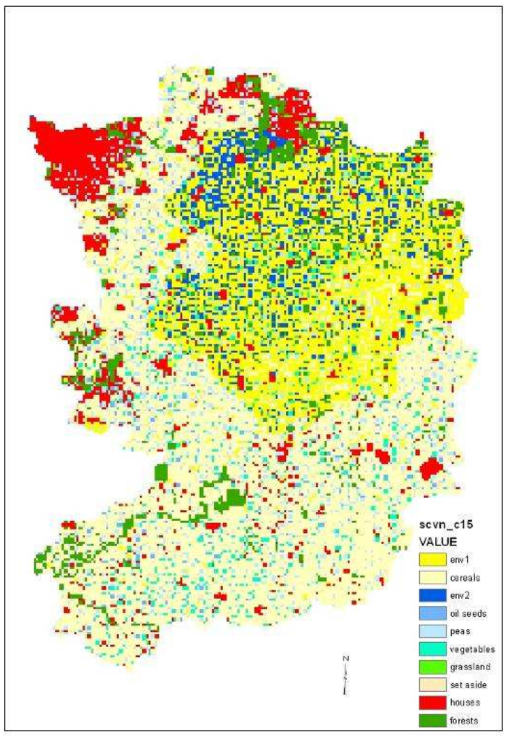
a.



b.



b.



c.

Figure 2.

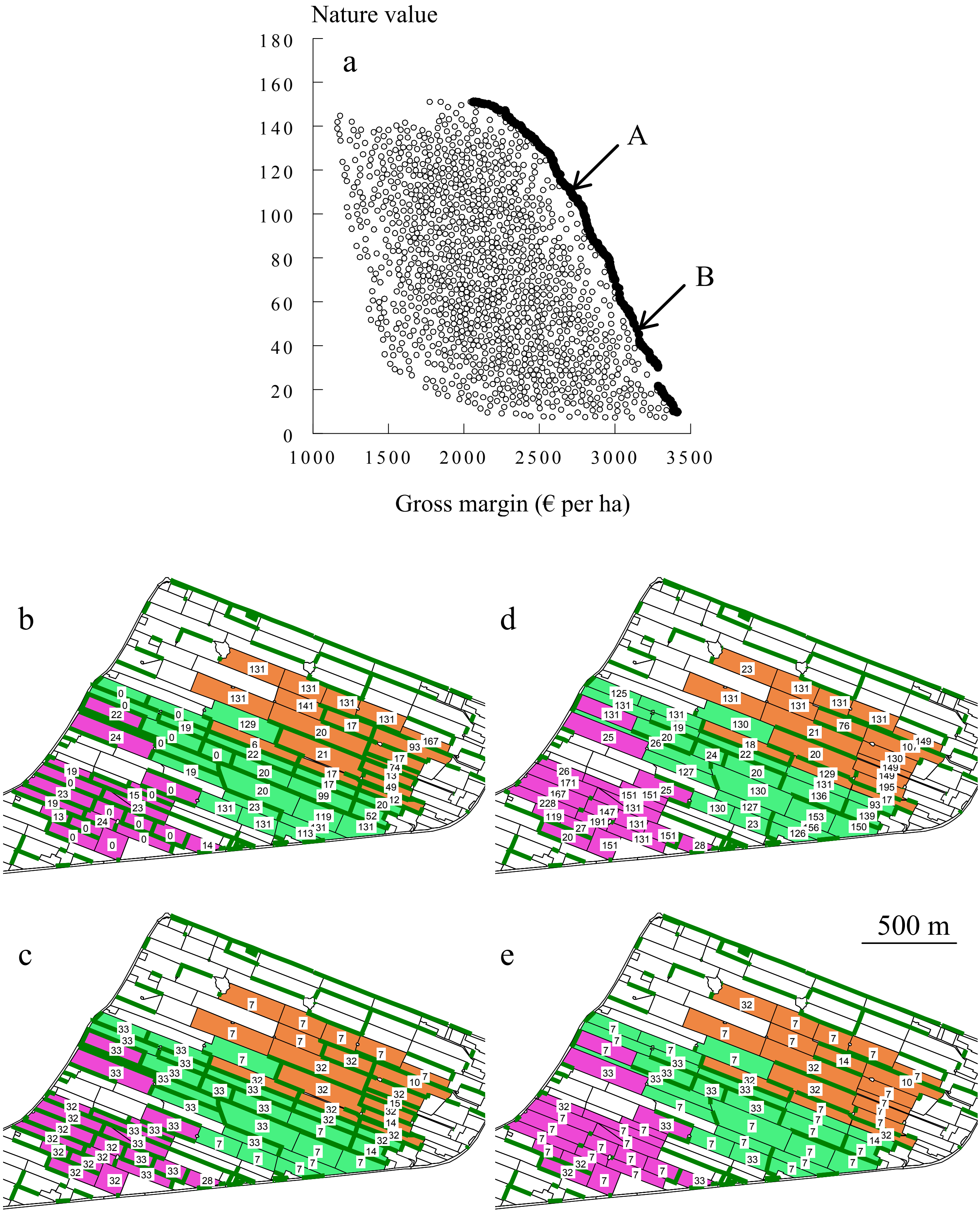
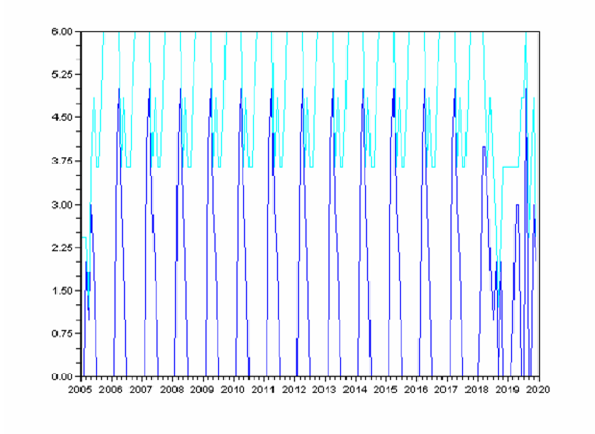
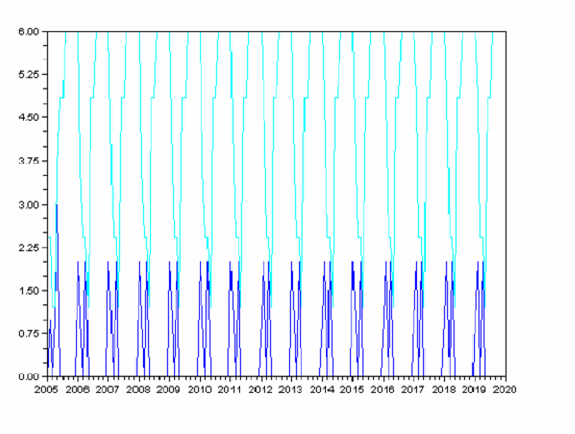

Nature value
a
180
160
140
120
100
80
60
40
20
0
1000
1500
2000
2500
3000
3500
A
B
Gross margin (€ per ha)
b
c
d
e
500 m

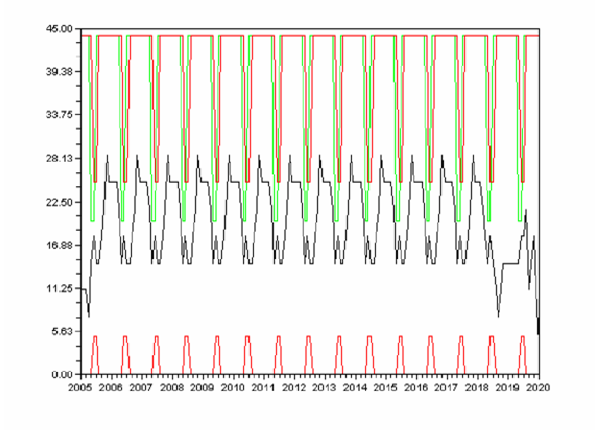
Figure 3.



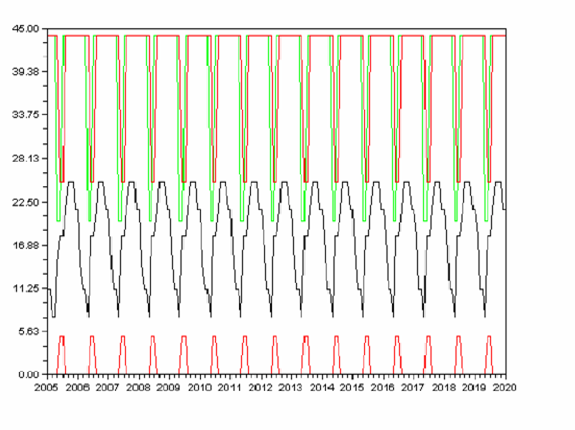
(a) Ecologic grazing $u_{ecol}(t)$



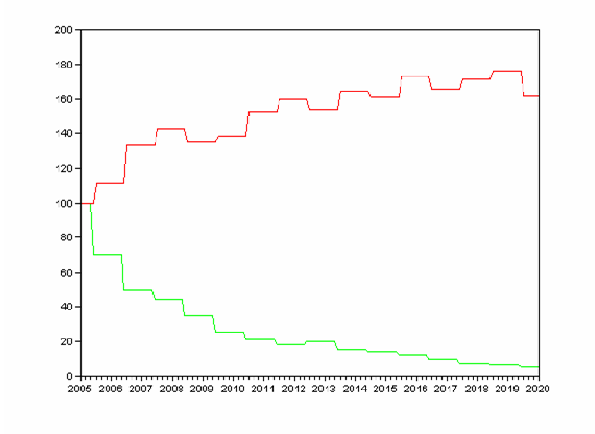
(b) Economic grazing $u_{econ}(t)$



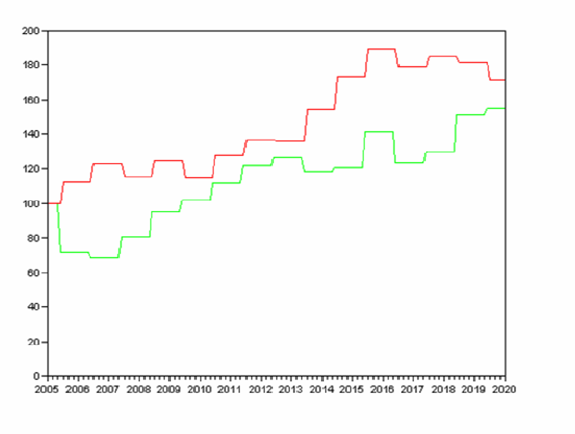
(c) Sward height $h_{ecol}(t)$



(d) Sward height $h_{econ}(t)$



(e) Wader populations $N_{ecol}(t)$



(f) Wader populations $N_{econ}(t)$

Figure 4.

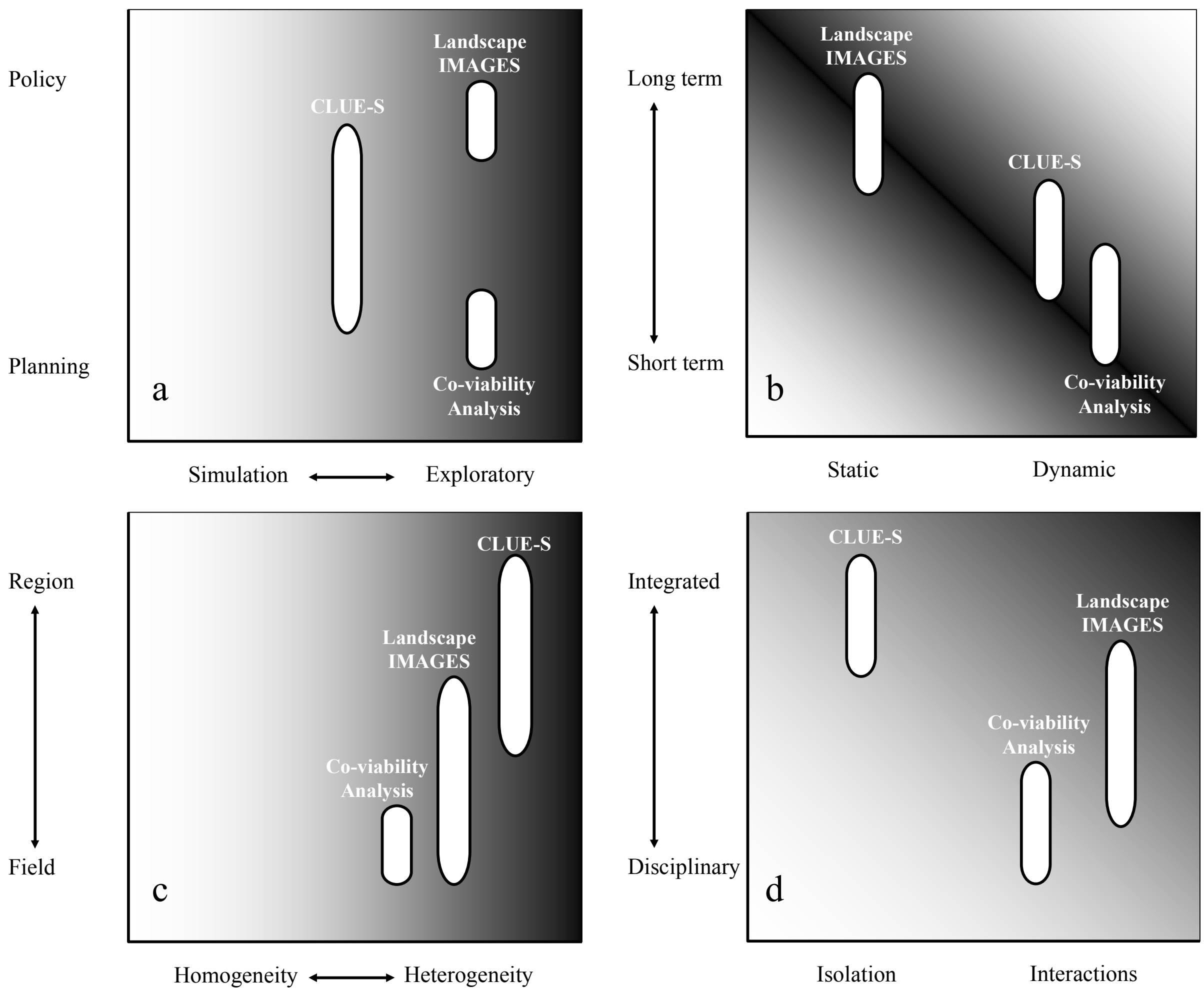

Policy
Planning
Landscape IMAGES
CLUE-S
Co-viability Analysis
a
Simulation
Exploratory
Long term
Short term
Landscape IMAGES
CLUE-S
Co-viability Analysis
b
Static
Dynamic
Region
Field
CLUE-S
Landscape IMAGES
Co-viability Analysis
c
Homogeneity
Heterogeneity
Integrated
Disciplinary
CLUE-S
Landscape IMAGES
Co-viability Analysis
d
Isolation
Interactions

Fig. 5.